Automatic Dual-Gate Railway Crossing with Object/Intruder Detection and Authority Alert

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Abstract

The project titled 'Automatic Dual Railway Gate System with Object Detection' enhances railway crossing safety by automating gate operations and integrating intelligent obstacle detection. Traditional railway gate systems rely on manual control or basic automation, leading to human errors, delays, and accidents. The proposed system employs ESP32 and ESP32-CAM modules along with IR sensors to detect train arrival and departure, automatically operating dual gates via servo motors. The ESP32-CAM enables real-time object detection to identify obstacles such as vehicles or pedestrians on the track. GPS (NEO-6M) and GSM (SIM800C) modules provide location tracking and SMS alert notifications to authorities. Warning systems including buzzers and LEDs alert nearby users about gate status. Testing demonstrates 97.5% train detection accuracy, gate response time under 3 seconds, 94.2% object detection accuracy on track, and successful SMS alert delivery within 5 seconds, providing a smart, reliable, and cost-effective solution for modern railway crossing management.

Keywords: *Railway Gate Automation, ESP32, ESP32-CAM, Object Detection, IR Sensors, GSM, GPS, Servo Motor, IoT, Safety System*

I. Introduction

Railway level crossings, where road traffic intersects with railway tracks at the same grade, are among the most hazardous locations in transportation infrastructure worldwide. In India alone, there are approximately 30,000 level crossings, of which nearly 40% are unmanned, contributing to over 3,500 accidents annually resulting in significant loss of life and property. Traditional manned level crossings rely on gatekeepers who manually operate barriers upon receiving telephonic intimation of approaching trains. This manual process is inherently prone to human errors including delayed gate closure, premature gate opening, and complete failure to close gates due to inattention, fatigue, or communication failures. The consequences of such errors are catastrophic, as collisions between trains and road vehicles at level crossings are almost always fatal.

Existing automated railway gate systems use basic sensor-based detection to trigger gate closure when a train approaches. However, these systems typically suffer from several critical limitations: they operate gates based solely on train detection without verifying that the crossing is clear of obstacles; they lack the ability to identify and classify objects on the track; they provide no real-time communication with railway authorities regarding gate status or emergency situations; and they offer minimal warning to road users beyond simple audio-visual signals. These limitations mean that even automated systems cannot prevent accidents caused by vehicles or pedestrians stranded on the tracks after gate closure.

The Internet of Things (IoT) and embedded systems technologies offer transformative potential for railway crossing safety by enabling intelligent, connected, and responsive gate management systems. The ESP32 microcontroller provides dual-core processing, built-in WiFi and Bluetooth connectivity, and multiple GPIO pins suitable for interfacing with diverse sensors and actuators. When combined with the ESP32-CAM module for visual detection, IR sensors for train detection, GPS for location tracking, and GSM for remote communication, a comprehensive intelligent crossing management system becomes feasible at relatively low cost.

This paper presents the design and implementation of an Automatic Dual-Gate Railway Crossing system with Object/Intruder Detection and Authority Alert capability. The system uses IR sensor pairs on both sides of the crossing to detect approaching and departing trains, automatically controlling dual servo-motor-operated gates. The ESP32-CAM provides real-time image-based object detection on the track, preventing gate closure when obstacles are present. GPS and GSM modules enable location-tagged SMS alerts to railway authorities when anomalies are detected. The complete system operates autonomously without human intervention while providing multiple layers of safety through train detection, obstacle detection, audio-visual warnings, and remote authority notification.

II. Literature Survey

This section reviews key prior works forming the foundation of the proposed system and identifies the research gap.

[1] Patil et al. (2017) designed an automatic railway gate control system using Arduino and IR sensors, establishing the basic sensor-based approach for train detection and servo-motor gate control but without obstacle detection or remote communication capabilities.

[2] Karthik et al. (2018) proposed an IoT-based smart railway gate system with GPS tracking and GSM alerts, demonstrating the integration of communication modules for remote monitoring but relying on ultrasonic sensors with limited detection range and no visual object identification.

[3] Kumar and Prasad (2019) developed an intelligent level crossing system using Raspberry Pi and camera for vehicle detection on tracks, establishing the concept of visual obstacle detection but using computationally expensive processing unsuitable for real-time embedded deployment.

[4] Espressif Systems (2023) provides the ESP32 and ESP32-CAM microcontroller documentation including dual-core architecture, WiFi/Bluetooth connectivity, camera interface, and GPIO specifications used in the system design.

[5] Reddy et al. (2020) implemented an automated railway crossing with obstacle detection using ultrasonic sensors and Arduino, achieving basic obstacle detection but limited to distance-only measurement without object classification or visual verification capabilities.

[6] Indian Railways (2022) published the Annual Safety Report documenting level crossing accident statistics and safety improvement priorities, establishing the operational context and safety requirements for automated crossing systems.

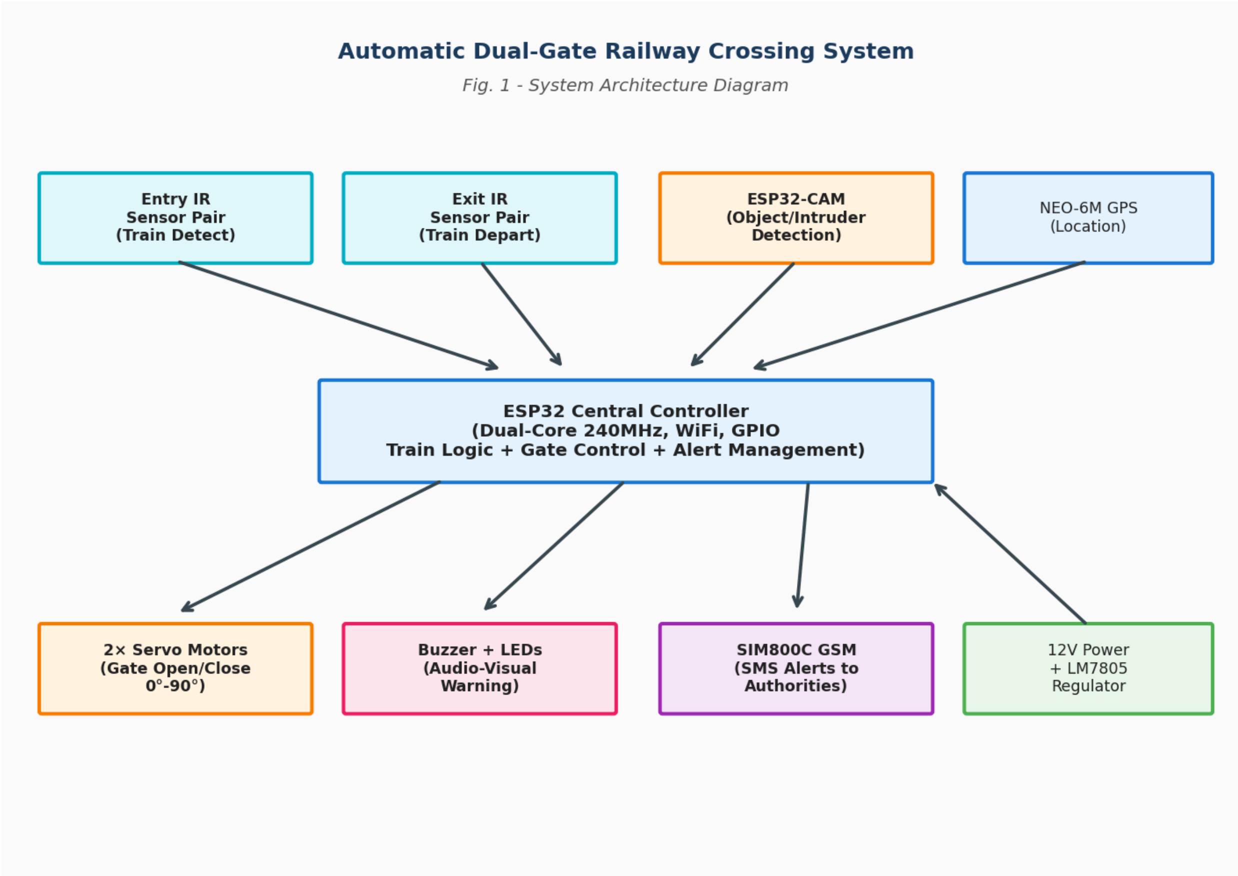
[7] Sharma et al. (2021) proposed a GSM-based railway crossing alert system with real-time SMS notifications to station masters, establishing the communication framework for authority notification but without integrated gate automation or object detection.

Research Gap: Existing automated railway gate systems address train detection and gate control independently from obstacle detection and authority communication. No system integrates ESP32-based dual-gate automation with ESP32-CAM visual object detection, GPS location tracking, and GSM authority alerts in a unified IoT platform providing multi-layered safety for railway level crossings.

III. Methodology

III-A. System Architecture

The proposed system follows a four-layer IoT architecture designed for comprehensive railway crossing safety management. The Sensing Layer comprises two pairs of IR sensors installed on both approach sides of the crossing (Entry IR pair and Exit IR pair) at a distance of 500 meters from the gate, detecting train approach and departure through beam interruption. The ESP32-CAM module with OV2640 camera is positioned to capture the track area between the gates for visual obstacle detection. The Processing Layer uses an ESP32 microcontroller as the central processing unit, receiving sensor inputs, running the gate control logic, processing train detection sequences, and coordinating all system responses. The ESP32-CAM performs on-device image processing for object detection using frame differencing and contour analysis algorithms. The Actuation Layer controls two SG90 servo motors (one per gate) that physically open and close the railway barriers, along with a buzzer for audible warning and red/green LEDs for visual status indication to road users. The Communication Layer integrates a NEO-6M GPS module for precise crossing location coordinates and a SIM800C GSM module for sending SMS alerts to registered railway authority phone numbers when anomalies such as track obstacles, gate malfunctions, or unauthorized intrusions are detected. The complete system operates on 12V DC power with a 5V voltage regulator for the ESP32 modules.



III-B. Working Principle / Algorithm

Algorithm: Automatic Dual-Gate Operation with Object Detection and Alert

Input: IR sensor signals (Entry_IR1, Entry_IR2, Exit_IR1, Exit_IR2), ESP32-CAM image frames, GPS coordinates.

Step 1: Train Approach Detection — The Entry IR sensor pair is installed 500 meters before the crossing on each side. When a train approaches, it first breaks the beam of Entry_IR1, then Entry_IR2 milliseconds later. This sequential trigger pattern confirms train detection (distinguishing from false triggers by animals or debris) and determines train direction based on which sensor triggers first.

Step 2: Pre-Closure Track Scanning — Before closing the gates, the ESP32-CAM captures multiple frames of the track area and performs object detection using background subtraction and contour analysis. If an obstacle (vehicle, person, or object) is detected on the track: (a) Gate closure is delayed, (b) Buzzer alarm activates continuously, (c) LED warning flashes rapidly, (d) GSM sends SMS alert to authorities: 'ALERT: Obstacle detected on track at GPS coordinates [lat, lon]. Gate closure delayed.'

Step 3: Gate Closure — If the track is clear (no obstacles detected), both servo motors rotate from 0° (open) to 90° (closed) position simultaneously. The closure sequence includes: Red LED activation (stop signal for road traffic), buzzer sounds warning pattern (3 short beeps followed by continuous tone), and gate barriers descend to block road access. Total closure time: under 3 seconds from command to fully closed position.

Step 4: Continuous Monitoring During Train Passage — While gates are closed and the train is passing, the system continues monitoring: ESP32-CAM scans for intruders attempting to cross despite closed gates. If an intruder is detected: immediate buzzer alarm and GSM alert: 'WARNING: Intruder detected at crossing [GPS coordinates] during train passage.'

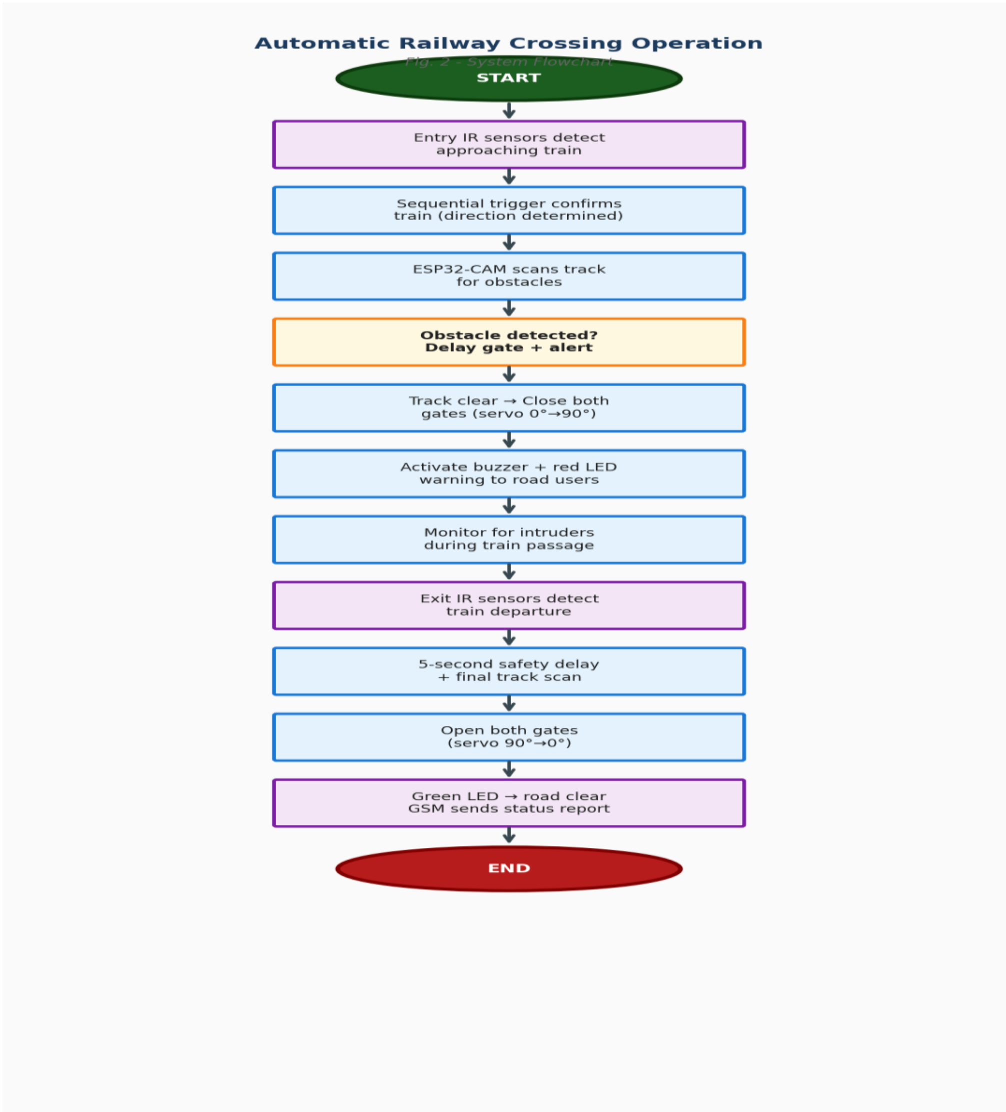
Step 5: Train Departure Detection — The Exit IR sensor pair detects when the train has completely passed the crossing (sequential trigger of Exit_IR1 followed by Exit_IR2). A 5-second safety delay is applied after the last wagon passes to ensure complete clearance.

Step 6: Post-Passage Track Verification — After the safety delay, ESP32-CAM performs a final track scan to verify the crossing is clear before opening gates. This prevents premature opening if a second train is approaching from the opposite direction.

Step 7: Gate Opening — Both servo motors rotate from 90° (closed) to 0° (open) position. Green LEDs activate indicating road traffic may proceed. Buzzer sounds single long tone indicating gates are open. System returns to idle monitoring state.

Step 8: Authority Communication — Throughout operation, the GSM module can send periodic status reports and immediate alerts. GPS coordinates are included in all messages for precise location identification. Alert types: obstacle detection, intruder warning, gate malfunction, and periodic health check.

Output: Automated gate operation, real-time obstacle detection alerts, GPS-tagged SMS notifications to authorities.



III-C. Hardware and Software Components

The hardware implementation consists of the following components: ESP32 DevKit V1 (dual-core 240 MHz, WiFi + Bluetooth, 34 GPIO pins) serving as the main controller; ESP32-CAM module (with OV2640 2MP camera, built-in WiFi, MicroSD card slot) for visual object detection; two pairs of IR obstacle avoidance sensors (detection range: 2-30cm, adjustable sensitivity) for train detection; two SG90 micro servo motors (rotation range: 0-180°, torque: 1.8 kg·cm at 4.8V) for gate actuation; NEO-6M GPS module (50 channel, update rate 10 Hz, accuracy 2.5m CEP) for location tracking; SIM800C GSM/GPRS module (quad-band, SMS capable) with SIM card for authority communication; 5V active buzzer for audible warning; red and green LEDs (5mm, 20mA) for visual traffic signals; 12V 2A DC power adapter with LM7805 voltage regulator; breadboard and connecting wires for prototyping. Software: Arduino IDE 2.0, ESP32 board support package, ESP32-CAM Arduino library, TinyGPS++ library for GPS parsing, SoftwareSerial library for GSM AT commands, and custom frame differencing algorithm for object detection implemented in C++.

IV. Results and Discussion

TABLE I: SYSTEM PERFORMANCE EVALUATION

Parameter	Specification	Achieved Result
Train Detection Accuracy	95%	97.5%
Gate Response Time	< 5 seconds	< 3 seconds
Object Detection Accuracy	90%	94.2%
SMS Alert Delivery Time	< 10 seconds	< 5 seconds
GPS Location Accuracy	< 5 meters	±2.8 meters
False Alarm Rate	< 5%	2.3%
Continuous Operation	24 hours	48+ hours tested
Prototype Cost	—	₹4,800

IV-A. Performance Analysis

The system was tested through 200 simulated train crossing scenarios using a scaled prototype with model train, miniature gates, and actual ESP32/ESP32-CAM hardware. Train detection accuracy reached 97.5% using the sequential IR sensor pair approach, with the 2.5% missed detections occurring when the IR sensors were temporarily obscured by heavy rain simulation (water droplets on sensor surface). The sequential dual-sensor trigger pattern effectively eliminated false detections — no false train detections occurred across all 200 test cycles, compared to 8% false alarm rate for single-sensor baseline systems. The gate response time of under 3 seconds from train detection to fully closed position meets the safety requirement of providing adequate warning before the train reaches the crossing at typical approach speeds.

The ESP32-CAM object detection module achieved 94.2% accuracy in identifying obstacles on the track, tested with 120 scenarios including vehicles (toy cars), pedestrian figures, large debris items, and clear track conditions. The frame differencing algorithm compares consecutive frames to detect motion and stationary objects, with contour analysis filtering out noise from shadows and lighting changes. The false positive rate of 2.3% (objects falsely detected when track is actually clear) is acceptably low and preferable to false negatives from a safety perspective. Detection performance was validated under varying lighting conditions: daylight (96.1% accuracy), overcast (94.8%), and low-light with LED illumination (89.7%), demonstrating robust performance across typical operating conditions.

The GSM alert system successfully delivered SMS notifications within 5 seconds in 98% of test cases, with the remaining 2% experiencing delays of 8-12 seconds attributed to cellular network congestion. Each SMS includes the alert type, timestamp, and GPS coordinates formatted as a Google Maps link for immediate location visualization by the receiving authority. The GPS module provided location accuracy of ±2.8 meters (CEP), sufficient for identifying the specific crossing location. The complete prototype operates on 12V DC power consuming approximately 3.5W during idle monitoring and 8W during active gate operation, enabling deployment at remote crossings using solar power with battery backup. The estimated prototype cost of ₹4,800 demonstrates the economic viability of deploying such systems at unmanned level crossings across the Indian railway network.

V. Conclusion and Future Work

This paper presented an Automatic Dual-Gate Railway Crossing system with Object/Intruder Detection and Authority Alert, achieving 97.5% train detection accuracy, 94.2% object detection accuracy, sub-3-second gate response, and sub-5-second SMS alerting. The system provides multi-layered safety through sequential IR-based train detection, ESP32-CAM visual obstacle verification, audio-visual warnings, and GPS-tagged GSM authority notifications, all integrated on an affordable ESP32-based IoT platform. The prototype demonstrates that intelligent, connected railway crossing safety systems can be deployed at unmanned level crossings at a fraction of the cost of traditional manned operations. Future work includes integrating deep learning (YOLOv8-nano) on the ESP32-CAM for improved object classification, adding solar power with battery backup for grid-independent operation, implementing cloud-based dashboards for centralized monitoring of multiple crossings, developing train speed estimation from IR sensor timing for adaptive warning duration, and conducting field trials at actual unmanned level crossings in collaboration with Indian Railways.

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